The subquantum arrow of time

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Emergent Quantum Mechanics 2013,
EmQM13, Vienna

To understand Nature
we have become accustomed
to inconceivable concepts …

Our task is to demystify physics

Setup

New insights from quantum measurement theory
The quantum measurement problem

Towards emergent QM
On the (quantum) vacuum

Stochastic electrodynamics (SED)
The subquantum arrow of time
Bell inequalities

The H ground state in SED

Fresh insights in Good Old QM

Allahverdyan, Balian, Nh, Physics Reports 2013:
"Understanding quantum measurement from dynamical models"
Solution of the Curie-Weiss model for Q-measurements:
Unitary dynamics of tested system S + *apparatus* A

Results:

Truncation of the density matrix (*decay of Schrodinger cat terms*)
Fast, physical process, due to coupling to A.

Registration: Pointer of A goes to a stable state, triggered by the measured value
Amplification of small quantum signal due to initial metastability of A

QM itself describes statistics of measurement outcomes;
no measurement postulates needed; no extensions of QM needed

Q-measurements lead to *statistical interpretation of QM*,
frequency interpretation of probabilities

The measurement problem

(a problem for theorists and philosophers)

How to describe the individual events observed in practice?
(How to go from wave theory to events?)

Quantum oddity: A mixed density matrix can be decomposed in any basis.
Why would measurement basis be preferred?

"Unsolvable" => many interpretations: Copenhagen, many worlds, mind-body
or extensions: spontaneous collapse models

Resolution by ABN'13:
Near the end of the measurement, *dynamical effects* in the apparatus make most decompositions of the density matrix *unstable*.

Only the decomposition on the measurement basis is dynamically stable.
So this is the physical basis. Arbitrary subensembles can be decomposed on this basis => connection to ordinary probabilities, frequency interpretation

Towards emergent QM

In Nature: separate measurements occur

We lack a theory that describes individual measurements

Look for “subquantum mechanics”, “hidden variables theory”

This task is more fundamental than the search for quantum gravity,

(and could have unpleasant surprises for it)

On the (quantum) vacuum

The Casimir effect is a *real* effect
Boats in harbours "attract each other" because few waves fit in between them

Suppose: Quantum vacuum = real physical vacuum
Zero point fluctuations due to real fields, which induce q-behavior

Up to which energy is the vacuum filled? If not up to the Planck energy,
quantum gravity is useless, string theory can only be an effective theory

Picture: vacuum fields gets created *after* the beginning of the Universe.
Maximal filling energy below Planck energy => non-quantum behavior at Planck scale

Vacuum energy (and pressure) are borrowed from gravitation.
Cosmological constant protected by energy conservation; fine tuning needed. (N'11)

Particles are *solitons*, affected by vacuum fluctuations
=> *Stochastic soliton mechanics* underlies quantum mechanics

Stochastic Electrodynamics, SED

Vacuum = stochastic EM fields, energy per mode $\frac{1}{2}\hbar\omega$, spectrum $\frac{\hbar\,\omega^3}{2\pi^2 c^3}$

Classical theory, explains many quantum properties (talk Cetto)

Empty vacuum + SED spectrum = Lorentz invariant physical vacuum

(Minkowski space-time + SED spectrum = Minkowski space-time)

This must explain *all* quantum behavior of atoms and molecules

Zero adjustable parameters, *“infinitely” many* constraints

Example: the H atom in SED

Electron in classical Kepler orbits

It radiates away energy, would fall onto nucleus

It absorbs energy from fluctuating vacuum EM fields
=> goes to other Kepler orbit. Statistics should produce ψ_0.

If there is a stable state, there is input+output of energy:
energy throughput, current of energy to maintain stable state.

But this is an *arrow of time*

The subquantum arrow of time

If there is a classical-type picture of the hidden variables theory, then a throughput of energy imposes quantum stability

This implies an arrow of time

This arrow is more fundamental
than the thermodynamic and cosmological ones

Bell Inequalities ??

Bell inequalities involve non-commuting variables

Hence these are measured one-by-one (Clauser, Aspect)

Next, they are inserted in an inequality meant for commuting variables

When the inequality is violated, it cannot apply to this situation:
There is a *contextuality loophole*, which cannot be closed
(Related to the detectors and the vacuum)

The only conclusion is that QM works.
Not any implication on local realism. *N'11*

SED: the H ground state

Pro: radiation and stochastic terms have desired scaling with α and *Z*
Leading logarithm of Lamb shift comes out in 2 lines

Contra: *Fokker-Planck approximation* (2nd order in stochastic field) *fails*
The theory is considered false, even by most advocates

Cetto & de la Pena: resonances appear beyond 2nd order, induce q-behavior

N'13: Higher order corrections in stochastic field, smaller by powers of α, develop arbitrary powers of *t*, due to (higher order) resonances

Conclusion: *perturbation theory fails, the case is still open*

Cole-Zou 2003: simulation of H ground state

Long box with $L_x = L_y = 70a_0, \quad L_z \sim 10^6 a_0$

$\Rightarrow$ stochastic EM fields in *lowest x-y mode; many z-modes*

Periodic boundary conditions => linear spectrum, $\omega = c|k_z|$

In atomic units $\ddot{\mathbf{r}} = -\frac{\mathbf{r}}{r^3} + \mathbf{E} + \dot{\mathbf{r}} \times \mathbf{B} + \tau_e \dddot{\mathbf{r}} \qquad \tau_e = \frac{2}{3}\alpha^3\tau_0$

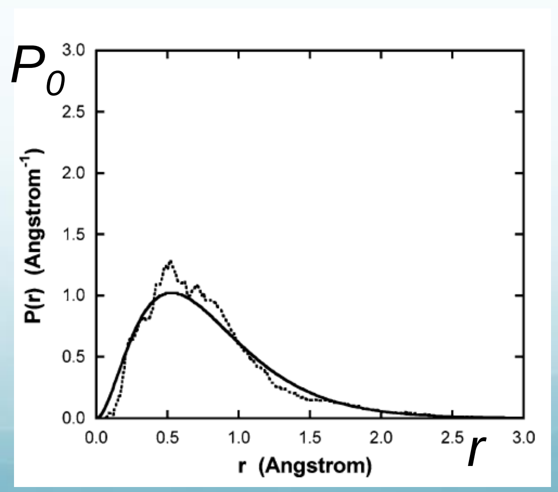
Neglect magnetic fields => motion in *x-y* plane

Resonances occur, they bring *e* to other Kepler orbits

Cole & Zou, 2003

Encouraging similarity to quantum result

$$P_0(r) = 4r^2\, e^{-2r}$$



Simulations anno 2013 at the University of A'dam

M. Liska,
E. van Heusden

Solve in-plane motion up to 10^5 Bohr times

Remains cumbersome. Electron often evaporates or falls into nucleus

No definite conclusion reached

But wait,

Coupling of *e* to EM fields shifts them; this generates the damping term.
The damping is geometry dependent

In long box:
standard damping

$$\tau_e \dddot{\mathbf{r}} \to -\gamma \dot{\mathbf{r}}$$

$$\gamma = \frac{2\pi\alpha^3 Z^2}{\tau_0}\frac{a_0^2}{L_x^2} = \frac{9\,10^{-6}}{\tau_0}$$

situation
Cole-Zou

Orbit remains in *z=0* plane $\ddot{\mathbf{r}} = -\frac{\mathbf{r}}{r^3} + \mathbf{E} - \gamma\dot{\mathbf{r}}$

Numerically: problems remain

Protocol for H ground state

Consider the nearly-conserved quantities

E = energy
L = angular momentum of in-plane motion
λ = angle of Runge-Lenz vector

Integrate them analytically over one orbit, iterate this numerically

Work in progress

What are we looking for?

2d H ground state $\psi_0^2(r) = \frac{8}{\pi} e^{-4r}$

In classical approach with weak noise: *density in phase space = f(E,L)*

N'05

$$P_0(\mathbf{p},\mathbf{r}) = \frac{8}{\pi^2 E^2} e^{4/E} \qquad \int \mathrm{d}^3 p \, P_0(\mathbf{p},\mathbf{r}) = \frac{8}{\pi} e^{-4r}$$

Parameters Kepler orbits distributed uniformly in *L*

$$P(E,L) = \frac{32\sqrt{2}}{|E|^{7/2}} e^{4/E}$$

Summary

QM does not describe individual measurements
They do occur, so an underlying less-statistical theory must exist

Local, classical picture may underlie quantum mechanics
Many constraints, no free parameters

Bell inequalities do not rule that out,
contextuality loophole cannot be closed

Atomic stability then implies a "subquantum" arrow of time;
more fundamental than thermodynamic and cosmological arrows

Structure of H ground state in SED is studied, work in progress

Quantum mechanics of hydrogen atom: nucleus charge = -Ze

Spectrum: Rydberg energy $\alpha^2 Z^2 mc^2$

Relativistic corrections $\alpha^4 Z^4 mc^2$

Lamb shift $\alpha^5 Z^4 mc^2 \log \alpha Z$

Relativistic spectrum for *m=c=1*

$$E_{n,l} = \{1 + \frac{\alpha^2 Z^2}{[n - l - \frac{1}{2} + \sqrt{(l+\frac{1}{2})^2 - \alpha^2 Z^2}]^2}\}^{-1/2} \approx 1 - \frac{\alpha^2 Z^2}{2n^2} - \alpha^4 Z^4 [\frac{1}{n^3(2l+1)} - \frac{3}{8n^4}]$$

Lamb shift: not from Schrodinger equation,
but due to coupling to EM field

weak effect $\Longrightarrow$ weak coupling, weak Lorentz damping

Weak damping classical stochastic theories for hydrogen atom

Phase space density $P(\mathbf{r},\mathbf{p},t) = \langle \delta(\underline{\mathbf{r}}(t) - \mathbf{r})\delta(\underline{\mathbf{p}}(t) - \mathbf{p})\rangle$

Evolution $\partial_t P = -\mathcal{L}P + Lorentz\ damping + diffusion\ terms$

$$\mathcal{L} \equiv \frac{1}{\gamma}\mathbf{p}\cdot\nabla_{\mathbf{r}} - \frac{\mathbf{r}}{r^3}\cdot\nabla_{\mathbf{p}}$$

Stationary distribution = function of conserved quantities

Energy $H = \sqrt{1+\alpha^2 Z^2 \mathbf{p}^2} - \frac{\alpha^2 Z^2}{r} = \gamma - \frac{\alpha^2 Z^2}{r}$

Angular momentum $L = r \times p$

The unsquared dance

Define R(E) by

$$E = \sqrt{1 + \frac{\alpha^4 Z^4}{R^2}} - \frac{\alpha^2 Z^2}{R} = \left(1 + \frac{2\alpha^2 Z^2}{RE}\right)^{-1/2}$$

Then non-relativistic problem

$$\frac{1}{2}\mathbf{p}^2 - \frac{\alpha^2 Z^2}{2r^2} - \frac{E}{r} = -\frac{E}{R}$$

Effective angular momentum

$$\omega = \sqrt{1 - \frac{Z^2\alpha^2}{L^2}}, \qquad \omega^2 L^2 = L^2 - \alpha^2 Z^2$$

In QM: effective angular momentum

$$\ell_l(\ell_l + 1) = l(l+1) - \alpha^2 Z^2, \qquad \ell_l = -\frac{1}{2} + \frac{1}{2}\sqrt{(2l+1)^2 - 4\alpha^2 Z^2} \approx l - \frac{\alpha^2 Z^2}{2l+1}$$

Bits and pieces

Go to cylindrical coords

$$p \Rightarrow (R, \mu, \nu)$$

$$\omega L = r\sqrt{2E\left(\frac{1}{r} - \frac{1}{R}\right)}\,\sin\mu, \qquad p_r = \sqrt{2E\left(\frac{1}{r} - \frac{1}{R}\right)}\,\cos\mu$$

Volume element in p-space

$$dV_p = \frac{d\mu\, d\nu\, dR}{2R^2\Phi(E)}\sqrt{\frac{2}{Er} - \frac{2}{ER}}\,\sin\mu \qquad \Phi(E) = \frac{\sqrt{1 + \alpha^4 Z^4/R^2}}{2E^2}$$

Consider

$$\mathcal{P}(E, L) = \omega L R^3 \Phi(E)\exp(-aR)$$

Then

$$dV_p\,\mathcal{P} = d\mu\, d\nu\, dR\,(R - r)e^{-aR}\sin^2\mu$$

Momentum integral

$$\int_{\mathbf{p}} dV_p\,\mathcal{P} = \frac{\pi^2}{a^2}e^{-ar}$$

= non-relativistic groundstate density

and the ratio

$$\frac{\omega^2 L^2 R}{2E} = r(R - r)\sin^2\mu$$

Generates a factor r

Yrast states: l=n-1 (maximal angular momentum)

Phase space densities

$$\mathcal{P}(R,L) = C\omega L R^3 \Phi(E) \left(\frac{\omega^2 L^2 R}{2E}\right)^{2\ell_l} e^{-2R\,E_{nl}/(\ell_l+1)}$$

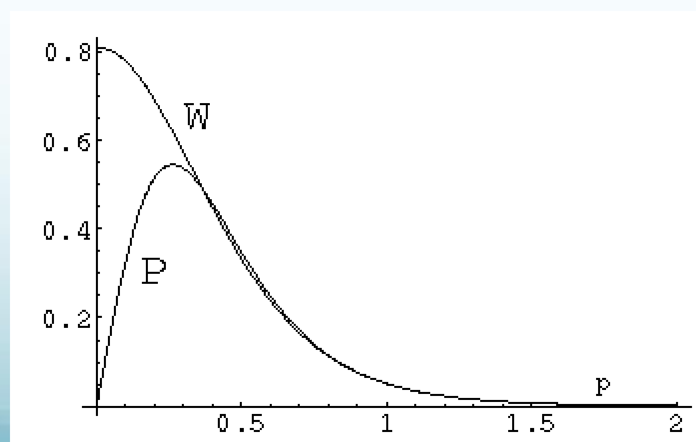
Momentum average gives square of wavefunctions:

$$\int_p dV_p \mathcal{P} = \int_{R,\mu,\nu} dV_p \mathcal{P} = \frac{2^{2+2\ell_l} E_{nl}^{3+2\ell_l}}{(1+\ell_l)^{4+2\ell_l}\Gamma(2+2\ell_l)} r^{2\ell_l} e^{-2r\,E_{nl}/(1+\ell_l)}$$

n=1: Ground state: P positive, so P differs from Wigner function

Reason: our p is instantanous; in Wigner function it is statistical

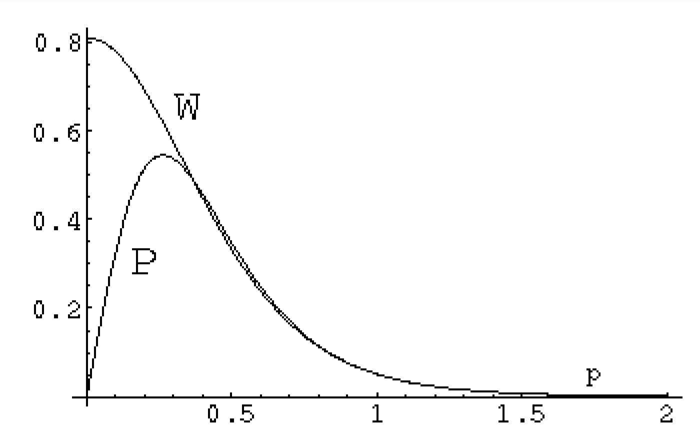
Space average



Wigner(p) versus Phase space density(p)

Test: scatter fast electrons on hydrogen atoms
(Mott & Massey: *Impulse approximation*)

Slow speeds: many revolutions during scattering: quantum cloud
Fast speed: instantaneous position and speed of bound e is probed



$> \alpha c$

Average energy

$$\langle E\rangle_{nl;\,cl} = 1-\alpha^2Z^2\langle\frac{1}{R}\rangle+\frac{1}{2}\alpha^4Z^4\langle\frac{1}{R^2}\rangle = 1-\frac{\alpha^2Z^2}{2}-\frac{(4n^2+4n-1)\alpha^4Z^4}{4n^4(8n^2-6n+1)} = E_{nl}+\frac{\alpha^4Z^4}{8n^4(4n-1)}$$

not correct ....

Doing the forbidden: Neglect correlations

Approximate $<\frac{1}{R^2}> \Rightarrow <\frac{1}{R}>^2$ then quantum mechanical energy recovered at order α^4

Do this at all orders $<\frac{1}{R^k}> \Rightarrow <\frac{1}{R}>^k$

$$\langle\langle E\rangle\rangle_{nl;cl} \equiv \sqrt{1+\alpha^4Z^4\langle\frac{1}{R}\rangle^2}-\alpha^2Z^2\langle\frac{1}{R}\rangle = \sqrt{1+\frac{\alpha^4Z^4E_{nl}^2}{4(1+\ell_l)^4}}-\frac{\alpha^2Z^2E_{nl}}{2(1+\ell_l)^2}$$

Exact quantum result regained for Yrast states:

$$\langle\langle E\rangle\rangle_{nl;cl} = \sqrt{\frac{(1+E_{nl}^2)^2}{4E_{nl}^2}}-\frac{1-E_{nl}^2}{2E_{nl}} = E_{nl}$$

2p state: spherical harmonics

In frame along r, cylindrical coordinates: L involves angles μ and ν

$$\mathbf{r} = r(\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta), \qquad \mathbf{L} = pr\sin\mu\,\hat{\mathbf{L}},$$

$$\hat{\mathbf{L}} = (-\cos\theta\cos\phi\sin\nu - \sin\phi\cos\nu, -\cos\theta\sin\phi\sin\nu + \cos\phi\cos\nu, \sin\theta\sin\nu)$$

Search phase space forms $Y^*_{lm} Y_{lm} \rightarrow \mathcal{Y}^{lm}_{lm}$

Proposal: $\mathcal{Y}^{1-1}_{1-1} = \frac{3}{4\pi}(\hat{L}_z^2 - \hat{L}_z), \qquad \mathcal{Y}^{10}_{10} = \frac{3}{4\pi}(1 - 2\hat{L}_z^2), \qquad \mathcal{Y}^{11}_{11} = \frac{3}{4\pi}(\hat{L}_z^2 + \hat{L}_z)$

a) $\int_0^{2\pi} \frac{d\nu}{2\pi}\mathcal{Y}^{11}_{11} = \int_0^{2\pi} \frac{d\nu}{2\pi}\mathcal{Y}^{1-1}_{1-1} = \frac{3}{8\pi}\sin^2\theta = |Y_{1\pm1}|^2 \qquad \int_0^{2\pi} \frac{d\nu}{2\pi}\mathcal{Y}^{10}_{10} = \frac{3}{4\pi}\cos^2\theta = |Y_{10}|^2$

b) $\overline{\hat{L}_z\,\mathcal{Y}_{1m;1m}} \equiv \int \sin\theta\, d\theta\, d\phi \int \frac{d\nu}{2\pi}\hat{L}_z \mathcal{Y}^{1m}_{1m} = m = \langle Y_{1m}|L_{z\,op}|Y_{1m}\rangle, \qquad (m = -1, 0, 1)$

Discussion

Considered class of theories includes Stochastic Electrodynamics

Phase space densities proposed for Yrast states l=n-1
Integral over p gives QM density
Integral over r does NOT give result from Wigner function
Test by scattering fast electrons on H

Different method, same result: consistency
Also 2s state considered: works in the same approach (non-unique)

l=1 phase space forms for squares of spherical harmonics proposed
Ground state density positive; excited states partially negative

Quantum energies recovered iff correlations neglected
Physically: time scale separation :
each new quantum operator corresponds to a classical average
at a well separated time $\Leftrightarrow$ subensembles de la Pena & Cetto

Theo's dream

1) Schrodinger mechanics = SED *de la Pena, Cetto, Cole, Khrennikov, ..*
2) Particles, photons: solitons in electro-gravity *Carter, Pereira, Arcos, Burinskii*
3) Physical explanation for exclusion principle and QM-statistics *timescales,*
4) QM = statistics of stochastic soliton mechanics *energetics*

This dream integrates basically all works of Albert Einstein.

Now you may say I'm a dreamer
But I'm not the only one
I hope one day you'll join us
And the world will be as one

Imagine, John Lennon

Quantum Mechanics
is a theory

that describes
the statistics
of outcomes
of experiments

It cannot and should not describe individual experiments
(otherwise than in a probablistic sense)